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Challenges of Transforming Coastal Buffer Zones into Urban Systems and their Sustainable Development Management: Case of Lake Issyk-Kul

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Abstract

The rapid growth of population, wealth, and increased demand for beach holidays, in parallel with climate change, have made coastal ecosystems the most vulnerable on the planet and require developing a well-thought-out plan for their sustainable management. The aim of this study is to investigate the state of coastal ecosystems of semi-desert zones, to identify the main factors of the destructive impact of anthropogenic load on these systems, as well as to predict the development of the situation at the local and regional levels and to develop preventive measures to mitigate existing risks. The study was conducted using Google Earth Pro and ArcGIS 10.5.1 software tools. In the research, the ecological state of natural coastal systems in the regions of semi-desert landscape was analyzed, and the dynamics of destructive consequences of the destruction of natural complexes depending on various factors of influence was presented, optimal and real for implementation measures for sustainable management of specific landscape complexes were developed to reduce the negative anthropogenic impact on the state of coastal ecosystems and public health, as well as to improve the overall environmental situation in the region. In addition, the possibilities of applying modern management and technological measures to minimize the load on the natural system, based on the synergy of environmental safety and economic efficiency, with the introduction of modern innovative control systems and monitoring environmental pollution have been studied. The results of the study have significant practical significance for the development and modernization of the system of sustainable management of natural complexes at the national and regional levels, creation of vector programs of preventive actions, as well as can be used as an effective tool for further analysis of the risks of negative consequences of anthropogenic impact on the balance in coastal ecosystems, biodiversity, and public health.

Keywords

Recreational area; Level of destruction; Influence factor; Ecosystem approach

Introduction

Coastal buffer zones (CBZs) are an effective and sustainable means of protecting aquatic ecosystems from nutrient run-off actively used in agriculture and thus act as a buffer against nutrient removal (Scholes, 2020). They deplete nutrients through soil adsorption, microbial immobilization, and plant uptake. Sandy shores devoid of vegetation cannot fully fulfill their ecological functions and pose a threat of the eutrophication of the water body. There is a need to find and develop a sustainable plan for the management and utilization of coastal ecosystems (Gao *et al.*, 2022). A sustainable development model should be drawn zone considering the natural zone's peculiarities, historical features, everyday life, and mores of the local population, defining specific boundaries of buffer zones, recreational zones, and mixed zones (Arunagiri *et al*., 2020).

However, holistic and integrated coastal management actions that protect the beach environment and its ecological processes have not yet been developed. The coastal zones with their beach and coastal dunes of semidesert and desert zones are especially relevant, which are particularly vulnerable and practically unrecoverable and, therefore, need special protection. It is necessary to allocate them to the especially vulnerable and untouchable zones (Theodora and Spanogianni, 2022). Scientists assert a noticeable trend of a sharp increase in beach tourism worldwide, attracting an ever-growing number of tourists to these ecosystems. This trend has led to a significant deterioration in the sustainability and quality of coastal ecosystems, a concern researchers emphasize (Balke *et al*., 2023; Brooks *et al*., 2020; Yin *et al*., 2022).

The increased ecological pressure on such systems is doubled by global climate change, in which their fragility and vulnerability are even more evident. Thus, such ecosystems are among the most vulnerable natural areas with an uncertain future. In such areas, there is a need to look for alternative ways of sustainable development, to consider and offer opportunities to benefit from ecosystem services to the local community, and to interest them in preserving the pristine beauty of the ecosystems. Once out of equilibrium, such systems cannot recover, and the destroyed vegetation cannot regenerate (Berdugo *et al*., 2020; Lian *et al*., 2021; Zhou *et al.*, 2022). One example of non-sustainable use of coastal ecosystems of semidesert zones is Lake Issyk-Kul — a brainless, deep-water lake characterized by contrasting natural zones. The average water temperature is from +21º to +23º in summer and about -4º in winter. The western part of the basin is arid, rain is rare, and snowfall is almost non-existent. Only 115 mm of precipitation falls in the western mountains fringing the lake, while the eastern shore receives about 600 mm. The intensive transformation of coastal ecosystems into beach areas has also affected the semidesert zones of the lake. From year to year, the areas covered with sea buckthorn thickets are decreasing, there is a massive development of holiday homes and resorts, and the construction of yurt camps along the buffer zone of the coast, which are not equipped with sewage systems, is also widely practiced (Kaptagaeva *et al.*, 2020).

Coastal buffer zones are often used as an environmental management tool to reduce the impact of land use on water resources. A buffer zone, area, or strip is generally defined as a strip of land separating uplands or hills from mountains, lakes, or wetlands (Schooler *et al.*, 2017). Land use in this area should be restricted to avoid adverse impacts on water quality, biota, and habitat within the catchment. Combining dense, hardy, and native

heat-loving grasses and woody plants dramatically enhances the effectiveness of dispersed pollutant removal. It is necessary to analyse the status of the lake's riparian buffer zones, assess their ecological condition and search for measures for their effective management (Lian *et al*., 2021).

The purpose of this study is to assess the ecological condition of coastal buffer ecosystems in the semi-desert regions of Lake Issyk-Kul using remote sensing and GIS applications to study the changes that have occurred. The study relied on Geographic Information System (GIS) and remote sensing data. In addition, we aim to explore opportunities for their sustainable development, balancing the needs of the local community with the ecosystem's innate capacity for self-regulation and self-renewal.

Materials and methods

Study area

The study area of Lake Issyk-Kul (Figure 1) is located between latitude (42°40′00″-42°10′00″) north and longitude (76°10′00″-78°09′00″) east. Issyk-Kul is a unique lake of significant ecological and scientific importance. It is a deep and salty lake in Kyrgyzstan and is mentioned to be a non-drainage lake, which means that its water is not discharged into other rivers. Thus, the lake water maintains its ecosystem and chemical balance through natural processes and water cycles in this region. Issyk-Kul is among the 30 largest lakes in the world by area and ranks seventh among the deepest lakes. Its location at an altitude of 1,608 meters above sea level has a significant impact on its climate and ecosystem. The total area of Issyk-Kul is 6,236 km^2, its length reaches 174 kilometres and width reaches up to 60 kilometres. The maximum depth of the lake is 704 metres and the average depth is 279 metres, which underlines its geological significance and its role in the hydrological cycle of the region. The lake receives its water from 116 rivers, making it an important factor in the catchment and storage of water resources in the region.

Since 2001, the Issyk-Kul Biosphere Region has been included in the UNESCO Planetary Network of Biosphere Reserves. This network was created to preserve the world's historical and cultural heritage through the protection of unique ecosystems. The Issyk-Kul Biosphere Reserve occupies a special place among the largest biological reserves in the world under the auspices of UNESCO and has the status of a specially protected natural territory of national importance. In 2002, Kyrgyzstan also joined the Ramsar Convention on Wetlands of International Importance. This emphasizes the importance of Issyk-Kul as a habitat for waterfowl and other forms of life, and the need to protect and sustainably use its natural resources.

Methodology

Three Sentinel-3 satellite images from May (2012), June (2017), and February (2022) were selected for the study of Lake Issyk-Kul. The characteristics of the images used to assess shoreline change should be of high quality and acquired during cloudless periods. May and June had cloudless times, which successfully achieved the objectives. However, the maps observed high snow cover levels in February. To improve the accuracy of the shoreline

change assessment and for data interpretation, a scale of 1:10000 was applied in this case, which contributed to obtaining accurate and correct data.

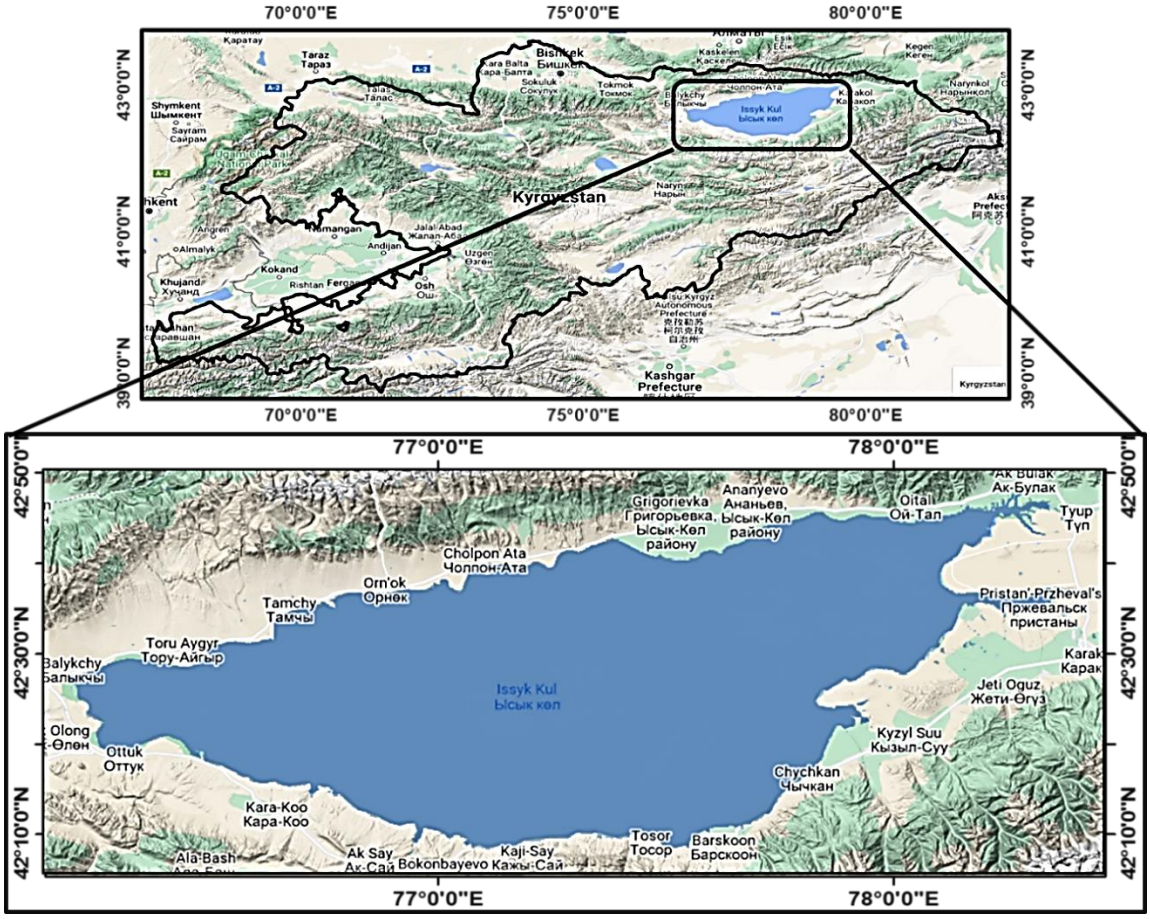


Figure 1: Study area

The delineation of the boundaries and areas of the coastal zones and the extent of their transformation was carried out using Google Earth Pro and ArcGIS 10.5.1. The areas of buffer zones at 100 m and 500 m from the lake shoreline and their changes for 2012, 2017, and 2022 were determined. The State Forest Cadastre of the Kyrgyz Republic determined the area covered by forest vegetation along the shoreline of Lake Issyk-Kul. The area of forest vegetation along the shoreline was calculated by the established boundaries of forestry farms along the shoreline (five forestry farms and one state nature reserve having forest land along the shoreline).

Results

Since 2000, there has been a tendency to decrease the area of riparian buffer lands at 100 m and 500 m of shore line (Table 1, Figure 1). Figure 1.a shows examples of conversion of two riparian buffer zones at a distance of 100 m (marked with a red line in the figures) in 2012, 2017 and 2021. Figure 1.b for 2010, 2017 and 2021.

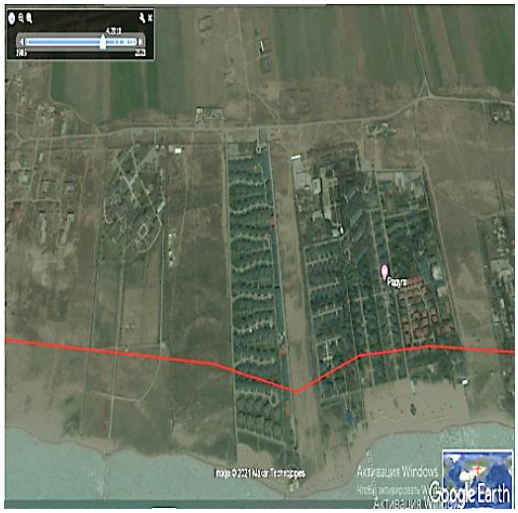
Table 1: Area of transformed coastal buffer zones (CBZ) at 100 m and 500 m ha

Transformation of CBZ		*2012*	*2017*	*2021*
Just 100 meters away, there are 2306 hectares of land				
Buildings at a distance of 100 meters		104.52	220.71	329.6
Just 500 meters away, there are 8551 hectares of land				
Agricultural land at a distance of 500 m		2429	2189.65	2116.4
Buildings at a distance of 500 m		446	663.78	910.09

Figure 2: Transformation of riparian buffer zones from 2010 to 2021

Figure 1a: Area at coordinates 1 42°38'26.46"C, 77°04'21.20"B in 2012

1st Photo/Figure 1a: Area at coordinates 2 42°38'26.46"C, 77°04'21.20"B in 2017
2nd Photo/Figure 1a: Area at coordinates 3 42°38'26.46"C, 77°04'21.20"B in 2021



1st Photo/Figure 1b: Area at coordinates 4 42°36'05.11"C, 76°56'12.10"B in 2012
2nd Photo/Figure 1b: Area at coordinates 5 42°36'05.11"C, 76°56'12.10"B in 2017

Figure 1b: Area at coordinates 6 42°36'05.11"C, 76°56'12.10"B in 2021.

As shown in table 1, coastal buffer zones have been decreasing significantly since 2010. At a distance of 100 metres from the shoreline, 14.5% of the buffer zone has been built up, and at a distance of 500 metres, 35.6% of the buffer zone has been built up, i.e., 64.4% are natural ecosystems. Considering that preserving 70% of ecosystems to maintain self-restoring capacity is recommended (Rotondo *et al.*, 2022), the excess of conversion is already 5.6%. In addition to developments, CBZs are being transformed into agro-landscapes, have been marked with a yellow line in figure 3 (Figure 3), creating conditions for biogens to enter the water. At such a rate, by 2065, CBZs may be completely transformed (Figure 4) (Kaptagaeva *et al.*, 2020).

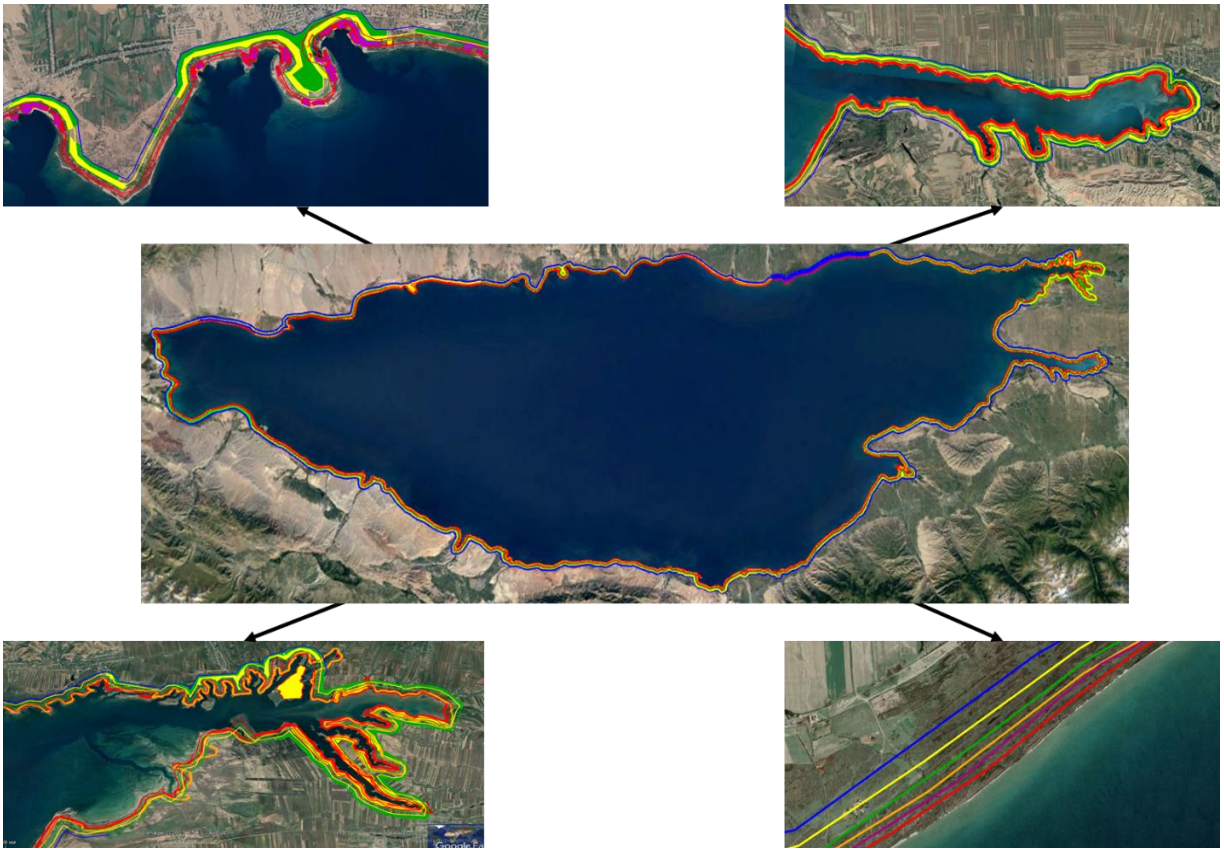


Figure 3: Scheme of Transformation of CBZ of Lake Issyk-Kul

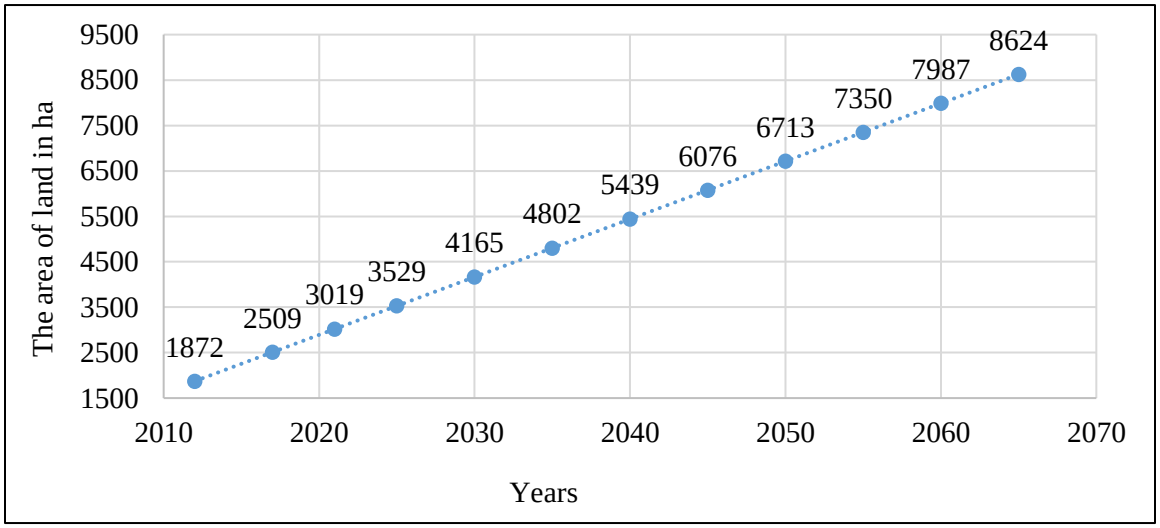


Figure 4: Forecast of CBZ transformation under the current trend of CBZ transformation

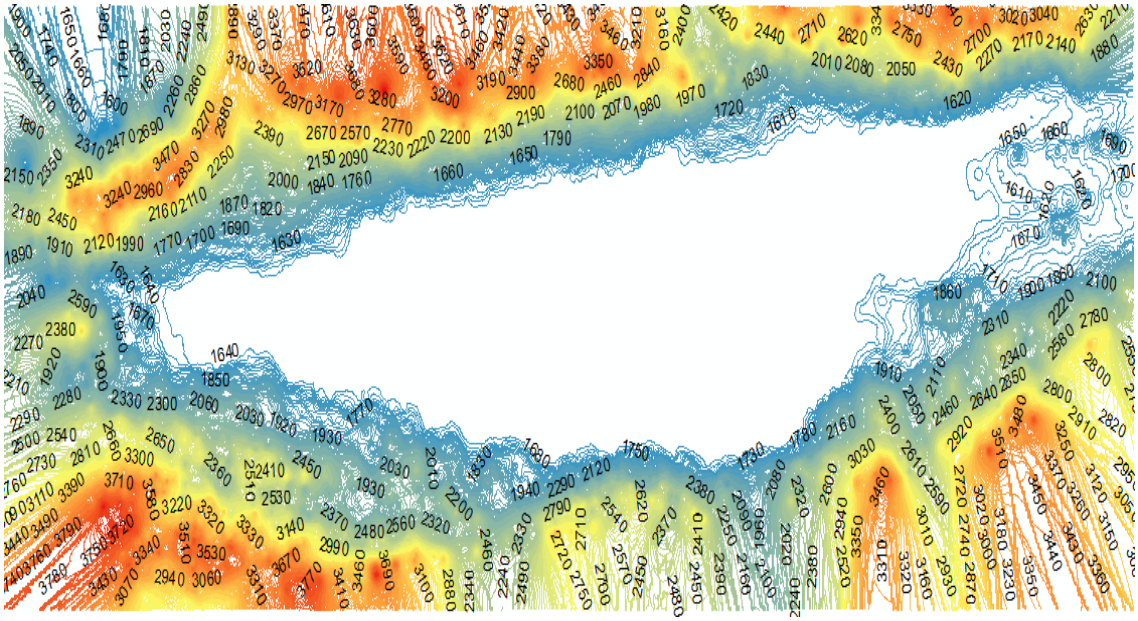


Figure 5: Points of the location of heights above sea level relative to the coastline

According to the analyses, riparian buffer zones are transformed for the following purposes: 104.52 in 2012, 220.71 in 2017, and 333.4 hectares of building area per 100 metres in 2021. In 2012, 2,429, 2,189.65 in 2017, and 2,135.18 in 2021 were used for arable land per 500 metres. In 2012 – 446, in 2017 – 663.78, in 2021 – 910.09 hectares of land for development (residential houses, guest houses, sanatoriums, cafés). The analysis shows that there is intensive development and transformation of coastal ecosystems of semi-desert zones. Sea buckthorn plantations are being cut down, which fulfill a great ecological function in preserving the purity of the lake water. In addition, they have an international status of wetlands, as they are wintering grounds for migratory birds (Kaptagaeva *et al.*, 2020).

Excessive transformation of the coastal buffer zones disturbs the ecological balance of the lake ecosystem, which leads to disturbance of the lake water quality (Kennish, 2022). According to studies cited in Abdiralieva and Totubaeva, (2023), the trophic status of the lake from ultra-oligotrophic gradually, in the most urbanized places, passes to mesotrophic state (Table 2). If in 2017, all the studied points had the status of ultra-oligotrophic, except for one point (Balykchy) - the status of which was oligotrophic, in 2022 the status of ultra-oligotrophic was not recorded, two points moved to mesotrophic status.

In ecological systems of coastal territories of semi-desert zones, as a result of long-term anthropogenic impact, there is a loss of biodiversity, there is a tendency to reduce the elasticity of ecosystems, resulting in a divergence of rates of vital functions of system elements, there is a direct impact on the structure of ecosystems as a result of the transformation of their components, which leads to disorganization of entire landscape complexes (Yang, Yang and Yu., 2018).

Pollution of soil cover and water resources with oil products and their ecological consequences testify to the exorbitant load on the ecosystems of the semi-desert zone.

Natural processes of self-purification cannot regenerate components of natural landscapes in the degradation process. In the progression of pressure on ecosystems in all components of natural landscapes of coastal zones, there is a continuous process of disturbance of ecological balance. The weak stability of coastal territories of semidesert zones is caused by low natural-resource potential, narrow homeostatic range, and low adaptive capacity. This region demonstrates the qualitative change of ecosystems, which has a systemic negative impact on all their components (Berdugo *et al.*, 2020; Mandle *et al*., 2021; Zedler and Kercher, 2005).

Table 2: Trophic index (by Carlson) of the studied sites

Address	*Range*	*TSI-2017 (average values: TN, TP, SD, Chl-a)*		*TSI-2022 (average values: TN, TP, SD, Chl-a)*	
Kadji-Say region	0.5 m	26.31	Ult-olg	36.42	Olig
Balykchy	0.5 m	32.72	Olg	45.31	Mesotr
Chok-Tal vil, № 11a	0.5m	27.63	Ult-olg	48.69	Mesotr
Choktal village,	0.5m	29.09	Ult-olg	43.86	Olig
Cholpon-ata,	0.5m	22.68	Ult-olg	40.67	Olig
Grigorevka vil	0.5m	24.55	Ult-olg	41.21	Olig
Bosteri village	0.5 m	28.62	Ult-olg	41.43	Olig

In this case, an integrated approach to addressing the situation is required within the framework of sustainable development programs and green economic courses. Sustainable management provides measures necessary for the protection and conservation of biodiversity, neutralization of the negative impact of industry on the environment, maximum elimination of pollution and regeneration of natural resources, and restoration of natural landscape complexes (Tang *et al*., 2023). In the process of active formation of the concept of sustainable development, the co-adaptive paradigm of nature management is becoming a priority. It implies the principle of compatibility of anthropogenic and natural components of the ecosystem, the implementation of which will ensure sustainable development of the system “society-natural environment” with minimal destructive processes and favourable conditions for regeneration. The essence of the co-adaptive concept believes in organizing landscape complexes so that the region functions as an integral sustainable system, where the compatibility of any anthropogenic load with the components of the natural environment of the natural landscape becomes a priority (Brooks *et al*., 2020). One of the ways of such organization is to optimize the functions of already existing riparian buffer zones, as well as to create new ones. In modern conditions, water protection zones should fulfil an irreplaceable role in preventing pollution and destruction of coastal territories. At the same time, the water system should be considered as a dynamic complex category (Berdugo *et al.*, 2020).

It is worth noting that landscape planning maps should be made on the basis of conjugate analysis of maps of planning limiting factors, allocated on the basis of a comprehensive assessment of the ecological state of the coastal zone. It should reflect functional zones of use of the whole territory, reflecting the main aspects: natural-spatial structure, economic development of the landscape, conservation objectives, and conflict areas of nature use (Tang *et al*., 2023; Yin *et al.*, 2022). Particular attention should be paid to the zones within the landscape that need special protection and have high value for the protection of biocenoses, individual species, unique natural resources, and are

representative. The main task for such functional zones is to preserve the interconnection of habitats with natural ecosystems, so it is necessary to ensure strict control over the absence of any use of natural resources, including extensive use (Zedler and Kercher, 2005; Zhou *et al*., 2022).

The second necessary component of the landscape complex of the coastal semi-desert territory should be the zone of preservation of intensively used habitats, the purpose of which should be to improve the natural environment in those areas where anthropogenic pressures pose a real threat to the existence of species and biocenoses. In such zones, it is necessary to create a structure of life support and economy that would minimally disturb natural processes Yang, Yang and Yu., 2018; Yin *et al*., 2022). The implementation of sustainable management tasks is ensured on the basis of bioindication data, ecobiomonitoring, and system analysis, as well as the formation of monitoring information technology, which anticipates the diagnosis, genesis, and forecasting of the state of the studied ecosystems. Such measures will make it possible to develop programs to restore the ecological functions of natural landscapes, which is an integral part of sustainable development programs (Brooks *et al.*, 2020; Wang *et al*., 2021; Yin *et al*., 2022).

Although the legislation provides for strict restrictions on nature use in the territories of water protection zones, in reality, many regulatory and legal provisions are not fulfilled. Analysis of the situation shows that riparian buffer zones can fulfil their environmental protection functions only in case of optimization of the system of management decisions to bring nature use in line with the requirements of the legislation. Considering the duration of economic use of the studied territories, the degree of development and the level of construction, it should be assumed that the solution of the problem will require significant time and economic resources. Among the priority practical measures to optimize the ecological condition of the coastal zones of semi-desert territories, the following should be highlighted:

— prohibition of discharge of untreated sewage water;
— limiting the use of pesticides and fertilizers in agricultural activities;
— optimization of the regional ecological network;
— creation of new additional coastal protection areas and repair of existing ones;
— freeing the buffer zone from illegal coastal constructions;
— reduction of anthropogenic load to the normative level.

The level of expediency and priority of these measures should be determined on the basis of the results of a comprehensive assessment of the state of the ecosystem, taking into account the multifactor interrelationships. Such an approach allows the realization of differentiated principles of management decision-making on protecting natural complexes, avoiding destructive processes in coastal zones, and improving the ecological situation and sanitary-hygienic condition of semi-desert ecosystems. Assessment of the state of ecosystems is, in essence, the process of determining the level of transformation of the natural system as the degree of deviation of the state of ecosystems from the initial original due to destructive processes in the structure and functions of biocenosis, hydrosphere, lithosphere, and other components. In this case, the term “state” refers to the position of an object in a selected coordinate system covering the entire area of existence of this object or a set of them, the total amplitude of its variability without destroying its structure (Brooks *et al*., 2020).

In practice, implementing such an approach seems very problematic in the context of large-scale disturbance of natural coastal ecosystems. To date, it is necessary to reconstruct the initial state at a specific date, after which the fundamental changes that led to the current state occurred, or it is essential to establish background areas for different ecosystems experiencing the least anthropogenic impact. In any case, the description of the state of ecosystems should take into account all the elements that make up the ecosystem (Abelson *et al*., 2020). It should be noted that the optimal basis for the implementation of adequate and effective environmental assessment of landscape complexes, including coastal areas of semi-desert zones, should be a modern system of monitoring environmental parameters as components of the local ecosystem. This type of monitoring currently exists either in an outdated, ineffective form or is absent at all. Consequently, analytics and forecasting of the state of the natural system will not be reliable without linking hydrological, geochemical, biocenotic, and other indicators of the landscape complex, as well as complete information on anthropogenic load and sources of pollutants. In this regard, a necessary precursor to implementing effective environmental assessment of coastal territories of semi-desert zones is an innovative approach to the monitoring system, covering the maximum volume of influence factors and vectors of anthropogenic impact (Planning, 2003). Besides, using informative bases of ecological monitoring, it becomes possible to draw up specific maps of the distribution of ecological sensitivity of coastal ecosystems of semi-desert zones in relation to predicted anthropogenic impacts, including with the help of geoinformation technologies. Implementing these measures will enable the development of proactive strategies and timely decision-making to mitigate the adverse effects on the ecosystem or its components. Besides, they will enhance our ability to respond effectively to emerging threats.

In order to solve the created problem of transforming coastal buffer ecosystems, especially semi-desert zones, into urban and agro-landscapes, it is necessary to offer alternative profit opportunities to the local population living near the coastal zones (Das *et al*., 2022). In fact, there is such an opportunity, and firstly, these are natural coastal complexes – sandy beaches, marshes formed in the zone of water outflow, and wild bushes on the shores of the lake. Here, in the ecosystems of buckthorn and bogs, a variety of flora and fauna live, forming a peculiar beauty and attracting with their charm. Buckthorn is the most common, but not the only, active filter element. The bogs have thistle, barberry, cherry-barberry, currant, and other species. Harnessing the innate resources available, promoting ecotourism while conserving the natural landscapes is essential. Developing the processing industry using local fruits of coastal vegetation is also advisable (López-López, 2021).

In addition, anthropogenic impact on the coastal recreational area should be organized taking into account natural patterns and established anthropogenic changes in natural ecosystems. All engineering solutions should be ecologically expedient (Kennish, 2022). In general, it is worth noting that the assessment of the level of disturbance of the ecological balance in the natural coastal system can be performed by analysing the changes in the state parameters of the elements of the coastal recreational zone: the rate of abrasive processes, the width of the beach, the risk of landslides, the level of pollution of soil, air, water resources, anthropogenic load, the presence, and condition of coastal protection structures (Noor and Abdul Maulud, 2022).

Discussion

The works of many scientists are devoted to studying the complex issues of formation, development, and transformation of the ecological state of coastal territories. Most of them note significant active interference in natural processes on such territories, with a frequent lack of proper scientific substantiation of technical solutions and compliance with existing normative documents in environmental safety (Zhou *et al.*, 2022). In the coastal zone, a special system of interrelations in space and time is formed between the territorial and aquatic components of coastal zones, which have a common geological basis and are closely connected by hydrolithodynamic processes (Zhao *et al*., 2006). Scientists emphasize that the increasing degradation and excessive utilization of resources in coastal areas demand scientifically grounded and ecologically safe technical and managerial solutions for developing such territories, taking into account local issues and functions (López-López, 2021). The analysis of approaches to assessing the ecological condition of coastal regions in semi-desert zones reveals a dual situation. On the one hand, a wealth of literature and research is dedicated to this issue in the scientific community. However, on the other hand, there is a need for the development of specific environmental criteria for designing landscapes in such areas, the systematic documentation of natural and human-induced patterns affecting ecosystem status and its components, the organization of a comprehensive engineering and environmental assessment process during construction and operation of facilities, and the incorporation of fundamental principles of sustainable development throughout every stage of assessment, monitoring, and implementation.

Among the key factors that can be used to conduct a comprehensive assessment of the ecological state of semi-arid coastal natural complexes, the following should be highlighted (Akamani, 2020):

- natural (tectonic, hydrometeorological, biocenotic, geological-geomorphological, hydrolithodynamic);
- anthropogenic (level of area change due to the violation of natural parameters, level of urbanization and disturbance of natural landscapes, level of change in the content of pollutants entering the soil and wastewater, level of atmospheric air pollution under the influence of stationary and mobile sources, indicators of change in the biodiversity of the landscape system);
- social (level of ecological culture and education, scientific potential, living standards and social tension, historical and cultural features of the region).

The presented groups of factors determine the ecological state of the coastal zone and form the features of the local situation in landscape ecosystems. Scientists propose to consider the natural characteristics of the territory as the first in importance as they determine the ecosystem's regeneration capabilities and the feasibility of using coastal zones in various spheres. At the same time, in the conditions of increasing environmental problems in landscape complexes of this type, natural factors and conditions of coastal territories of semi-desert zones should be assessed from the standpoint of determining their ecological state (Lian *et al*., 2021).

Many scientists argue that, in the future, a predominant role should be given to the comprehensive ecological assessment of the state of coastal areas, aimed at a thorough analysis of the situation and the preventive protection of causal relationships within the ecosystem. In this process, special importance should be placed on engineering-ecological research, recognizing that landscapes of this type are active areas for the manifestation of exogenous geological processes. Additionally, it is essential to implement a monitoring and control system, the results of which serve as the basis for effective forecasting and modelling using innovative technologies (Das *et al*., 2022). Mapping as a method allowing fixing the volumes of existing anthropogenic load on coastal ecosystems should be singled out separately. According to scientists, cartographic modelling using GIS technologies is one of the priority methodological bases for studying coastal landscapes and assessing their condition (Brooks *et al*., 2020; Wang *et al.*, 2021).

As a result of studies, as well as the current work, it was established that in the future, it is considered appropriate to focus on a gradual increase in the use of coastal landscapes as recreational areas or in the aspect of preserving them as protected natural complexes. The priority should be the gradual cessation of uncontrolled anthropogenic load on the components of ecosystems of coastal territories of semi-desert zones, i.e., isolation of the anthropogenic cycle from the natural one (Wang *et al*., 2021). It should also be noted that the optimization of the state of coastal zones anticipates the application of an ecosystem approach, as well as the introduction of integrated management of natural resources based on the principles of sustainable development. These conclusions are in line with the results of studies by many scientists (Fu, Liu and Meadows, 2023).

The ecosystem approach implies the inseparability of individual components of the ecosystem (soil, flora and fauna, atmospheric air parameters) among themselves and with the anthropogenic component. It, therefore, offers conceptual systemic management of the ecological environment in all interrelationships. Integrated management of the studied landscape complexes allows for effectively solving such strategic tasks as optimization of nature management, increasing the sustainability of coastal ecological systems, qualitative monitoring, and effective response to situations with environmental risks. The ecosystem approach allows creating an optimal balance between environmental protection, sustainable nature management, and distribution of benefits from resource use. They emphasize that processes within ecosystems often exhibit non-linear attributes and result in enduring consequences. According to the researchers, it is necessary to use adaptive management tools, the main goals of which are to preserve the structure and functions of the ecosystem, as well as the ability to manage the processes occurring in it. All decisions should be as decentralized, long-term, and based on sustainable management principles as possible, thus maintaining the productive potential of ecosystems, taking into account the specific individual characteristics of each case. (Yin *et al*., 2022).

Thus, the ecosystem approach to assessing the ecological state of coastal territories of semi-desert zones, in the concept of sustainable management, involves the following measures:

— development of ecosystem management objectives;

— effective utilization of scientific and technical capabilities in terms of ecosystem structure and function;
— integrated comprehensive assessment;
— integrated coordinated monitoring;
— a system of planning, decision-making, and consequence control;
— strategic modeling and forecasting.

Some authors suggest using the geometric mean function when constructing a generalized indicator of the state of coastal zone ecosystems in semi-desert regions, as it makes it possible to use a set of indicators without determining the significance of each, to bring indicators measured in different units to a single value, and to take into account the specifics of the dynamics of individual factors (Rotondo *et al*., 2022). In general, most researchers agree that the assessment of the ecological state of coastal zones should be based on a limited number of criteria that, when considered together, can provide an effective and reliable qualification of the state of the ecosystem. At the same time, a unified approach to the process of assessment of both the natural-anthropogenic system and its components is necessary. The reliability of the assessment results directly depends on the accuracy of fixing the determining factors and types of impact, which bear the maximum negative load on the ecological state of coastal territories of semi-desert zones.

It is necessary to use a range of modern methods, such as integral biological assessment of soil condition, coupled with the basin-landscape approach and modelling of geo-ecological situations. Such a synergy of innovative measures will make it possible to create an effective, sustainable development mechanism of natural and anthropogenic systems. In turn, this will make it possible to identify the most disturbed areas, objectively assess the degree of destruction, and create modern systems for optimal management with the aim of regeneration and preventive protection (Löbmann *et al*., 2022).

Conclusions

Today, the territories of natural ecosystems of coastal buffer zones are intensively shrinking, being transformed into agro- and urban landscapes. Conservation of unique coastal ecosystems, located near human settlements and experience significant anthropogenic pressure, requires consolidation of knowledge, experience, and political will. Reduction of riparian buffer zones leads to deterioration of the lake's water quality. For sustainable and long-term use of the lake for recreational purposes, it is recommended to preserve natural coastal ecosystems. It is unambiguous that in order to optimize the state of ecosystems of coastal territories of semi-desert zones, it is necessary to limit such activities that lead to chemical, radioactive, and other dangerous types of pollution of natural water bodies, as well as to control the state of domestic and industrial waste dumps, agricultural enterprises located in adjacent territories.

The suggested method for evaluating the condition of coastal ecosystems in semi-desert zones offers a practical way to integrate sustainable management principles into implementation programs. It enables the identification of key factors and parameters and the development of innovative approaches for monitoring and assessing environmental conditions at both local and regional levels. This approach involves a comprehensive

evaluation of ecosystem status, considering the optimization of technical solutions and preventive measures while taking into account the natural and human-induced patterns affecting the ecological condition of the areas in question. The priority task of modern society, which forms its activities on the basis of the principles of sustainable development, is to maintain ecological and socio-economic unity at all stages of functioning, as well as active regeneration and improvement of environmental parameters while minimizing environmental risks. An effective ecosystem management system can be formed only in the presence of complete and reliable information on various properties of ecosystems, their characteristics, and dynamics, as well as the ability to use the data obtained to develop rational management decisions optimally.

In this regard, assessing the state of ecosystems of coastal territories of semi-desert zones is an integral component of sustainable environmental management. It requires increased attention in drawing up regional and national environmental programs, forming preventive measures to prevent destructive processes, and using innovative modelling and forecasting capabilities. The possibilities of modern systems of monitoring, modelling, and forecasting the ecological state of coastal ecosystems of semi-desert regions, as well as determining optimal preventive solutions to prevent negative anthropogenic impact on the studied territories, require further research.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	Yes
Contributed to data analysis & interpretation	Yes	No
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	No
Editing of the article/paper	Yes	Yes
Supervision	No	Yes
Project Administration	No	Yes
Funding Acquisition	No	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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